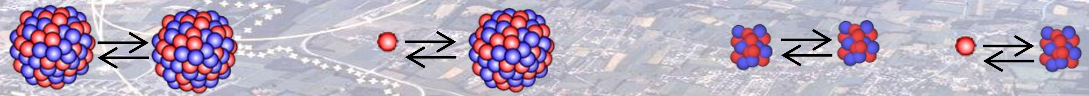
Ions - outlook for 2023 and beyond



R. Bruce, R. Alemany Fernandez, H. Bartosik, R. Cai, M. D'Andrea, J.M. Jowett, D. Mirarchi, F. Moortgat, B. Petersen, S. Redaelli, M. Solfaroli, J. Wenninger

Acknowledgements:

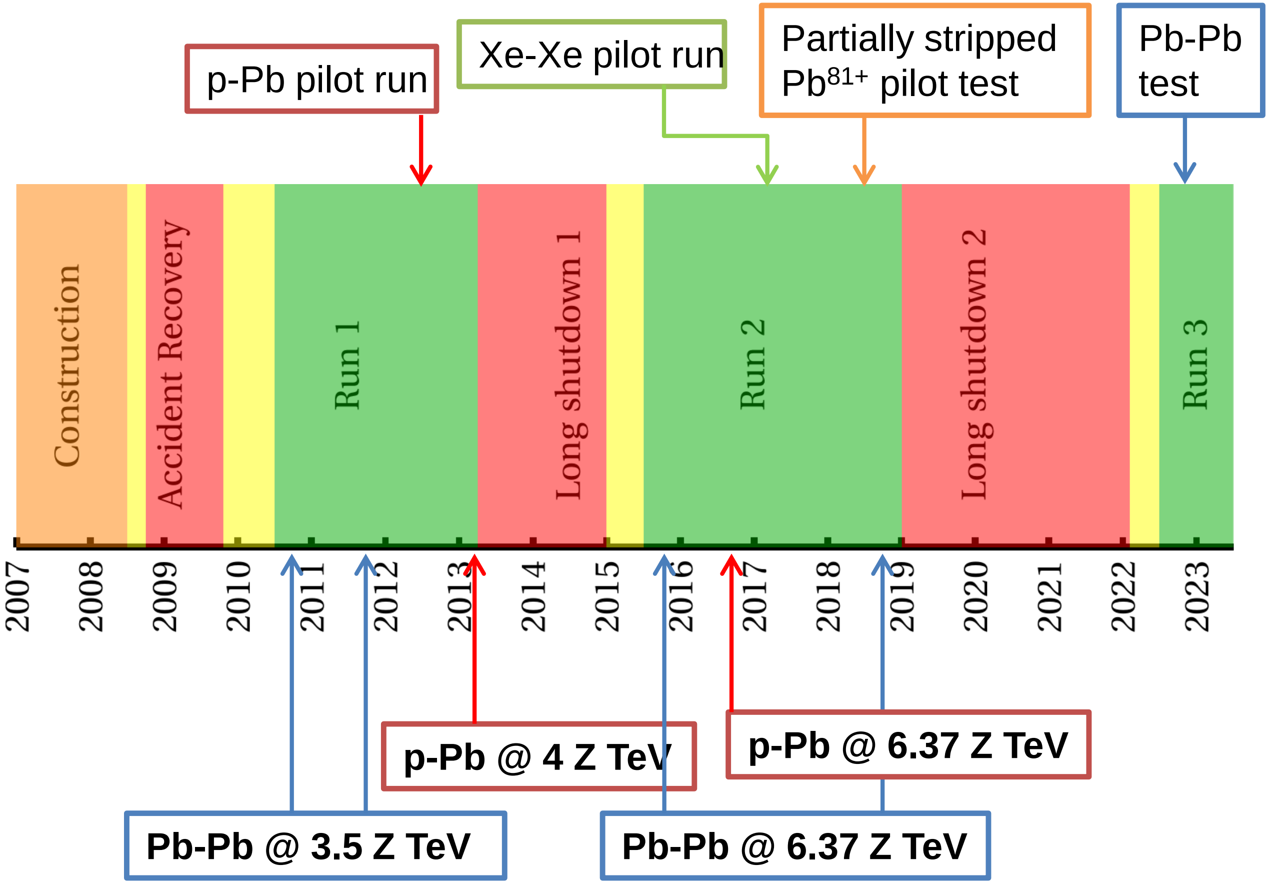
T. Argyropoulos, N. Biancacci, F. Boattini, C. Bracco, M. Calviani, H. Damerau, R. De Maria, M. DiCastro, S. Fartoukh, A. Frasca, N. Fuster-Martinez, C. Hernalsteens, P. Hermes, M. Hostettler, G. Iadarola, M.A. Jebramcik, S. Kostoglou, D. Kuchler, E. Matheson, N. Mounet, F-X. Nuiry, S. Paiva, Y. Papaphilippou, T. Persson, G. Rumolo, M. Schaumann, R. Scrivens, R. Steerenberg, G. Sterbini, H. Timko, R. Tomas, F. van der Veken, D. Wollmann

Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

History of heavy-ion runs in the LHC

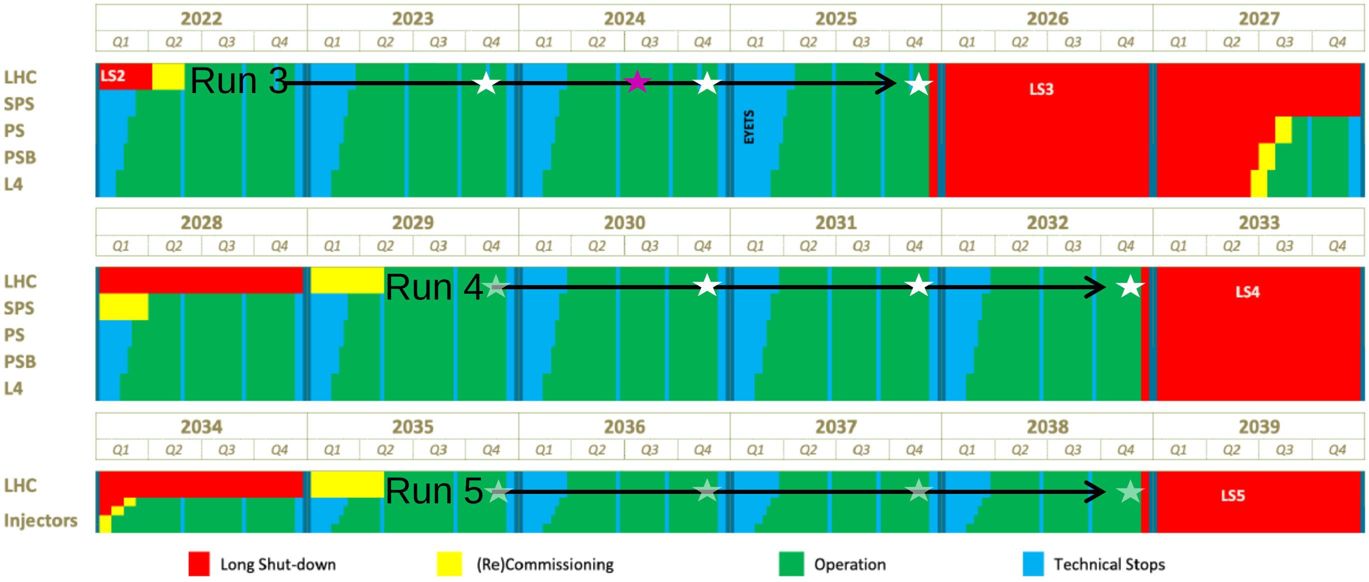
- **Typically one month per year with heavy-ion operation**
  - So far Pb-Pb or p-Pb
  - Six runs so far
- **In addition, had short "pilot runs"**
  - First p-Pb
  - Xe-Xe
  - partially stripped Pb81+ (no collisions)
  - Pb-Pb in 2022
    - 2022 Pb-Pb physics run cancelled



Future LHC heavy-ion operation

- In the future, continue with one-month ion runs at the end of the year
- 3 ion runs planned in Run 3, after cut of 2022 run
- Planning not yet fully fixed for Run 4
  - Having 4 ion runs would facilitate achieving the targets

Long Term Schedule for CERN Accelerator complex *EDMS: 2311633 v.2.0*



★ *Future heavy-ion runs? Detailed schedule still to be defined*

★ *Oxygen pilot run?*

Physics goals

- **Run 3+4 Pb-Pb physics goal: 13 nb^{-1} for ATLAS, ALICE, CMS**
  - Same goal as before 20% cut in physics time and cancellation of 2022 ion run
  - Needed 2.6 nb^{-1} per one-month run, assuming five runs in total, as before cancellation of 2022 run

- **2023 physics goals**
  - 3.25 nb^{-1} at ALICE
    - would give 13 nb^{-1} in four runs, as assumed after cut of 2022 ion run
  - 3 nb^{-1} at ATLAS/CMS
  - 0.4 nb^{-1} at LHCb

See talk F. Moortgat

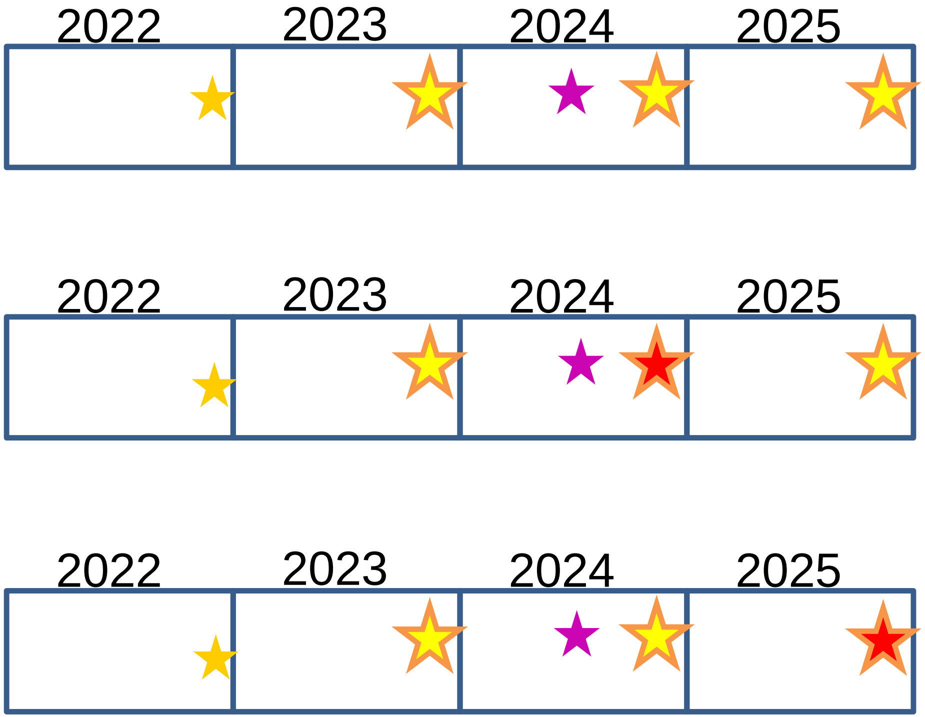
- **The goals are ambitious and challenging, given the recent cut in running time**

Ion operation in Run 3

- **Ion runs foreseen in 2023, 2024, 2025**
  - 2023: **Pb-Pb**
  - 2024-2025 : Pb-Pb only, or one year of p-Pb if it is found that Run 3 target can be reached with only two Pb-Pb run
    - If so, will likely have 5 weeks Pb-Pb runs and and 3 weeks p-Pb

- **1-week O-O and p-O pilot run likely in 2024**

Options for ion operation in Run 3



★ Pb ion test

★ Pb-Pb

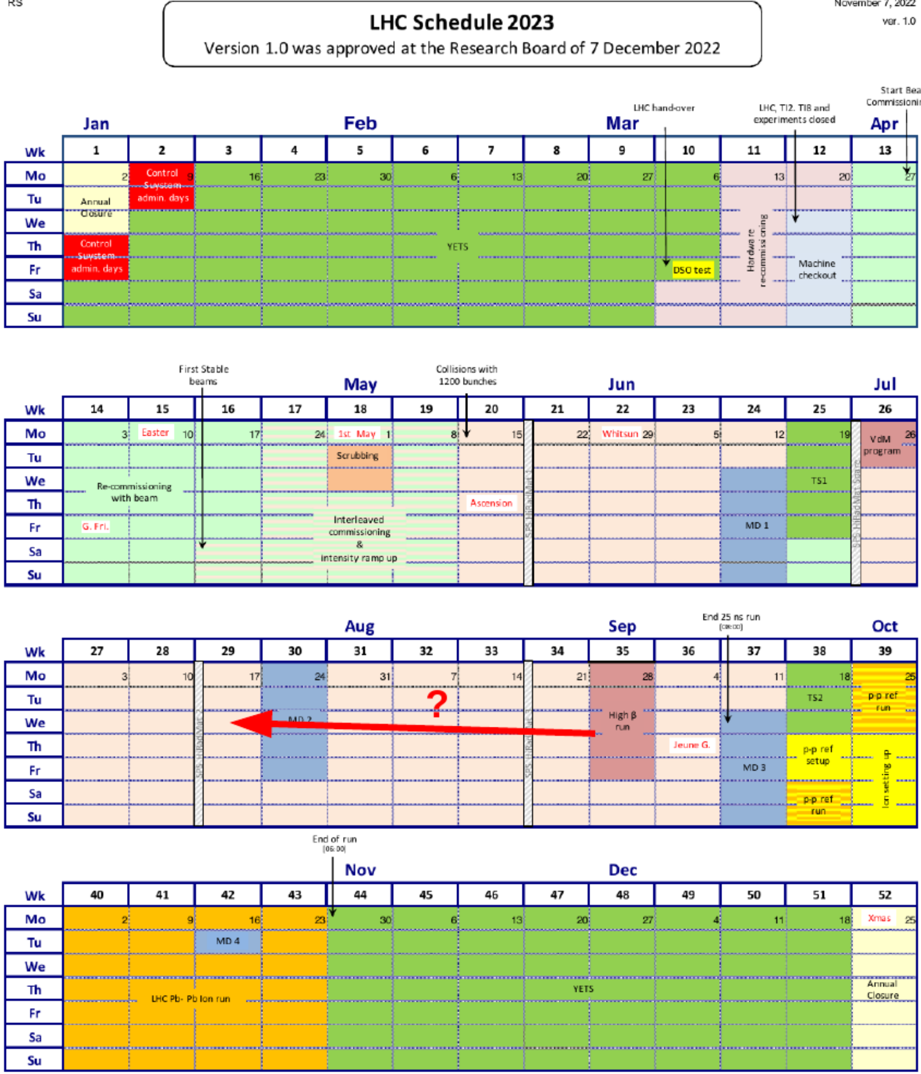
★ p-Pb

★ O-O, p-O: ~ 1 week

Outlook for 2023

- **LHC 2023 schedule: Pb-Pb run foreseen in October**
  - 1 week pp reference run
  - 4 days Pb commissioning
  - 27 days of Pb-Pb physics operation
  - 1 day of MD

- **pp-reference run: Details being worked out**
  - Beam energy given by main Pb run: if 6.8 Z TeV,p energy will be 2.68 TeV



Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

LHC upgrades

- **Reminder: all HL-LHC upgrades for ions have already been implemented in LS2**
  - Crystal collimators
    - Needed for handling beam losses with the higher intensity
    - Two devices replaced in LS2, the remaining two replaced in 22-23 YETS – completely new system compared to Run 2
  - IR2 dispersion suppressor collimators
    - Intercept collision products to enable higher instantaneous ALICE luminosity
  - Slip-stacked beams with 50 ns spacing thanks to SPS RF upgrade
    - Gives ~70% more bunches

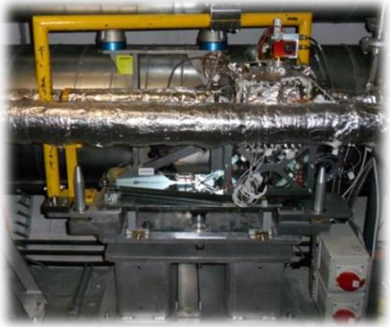
- **In addition, upgraded ALICE detector to handle higher event rate**

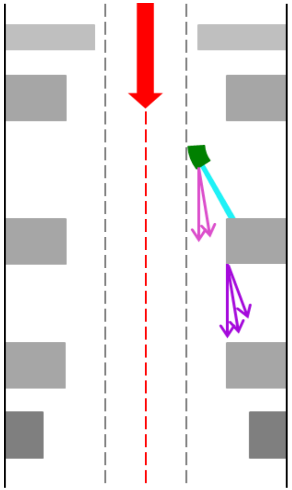
- **Thanks to these upgrades, hope to have HL-LHC-like performance already in Run 3**

Crystal collimation

- **Future ion runs rely on crystal collimation**
  - Increased cleaning performance to increase availability in presence of lifetime drops at higher intensity
    - Several dumps in 2018 due to “10 Hz losses”
  - Keep standard collimation hierarchy for machine protection
    - See talk D. Mirarchi

- **Good performance demonstrated with crystals, but still some uncertainties on machine availability due to beam losses**
  - Will the 10 Hz losses still be there? How long will losses last, and what will the peak loss rates be?
  - Crystals provide a sizeable gain in cleaning, but is it enough?
  - Very good experience with the two LS2 crystals – will the two new crystals installed in 22-23 YETS perform equally well?
    - Important to commission them early on with protons
  - How is the reliability and reproducibility of cleaning performance over long-term periods?





Collimation and beam energy

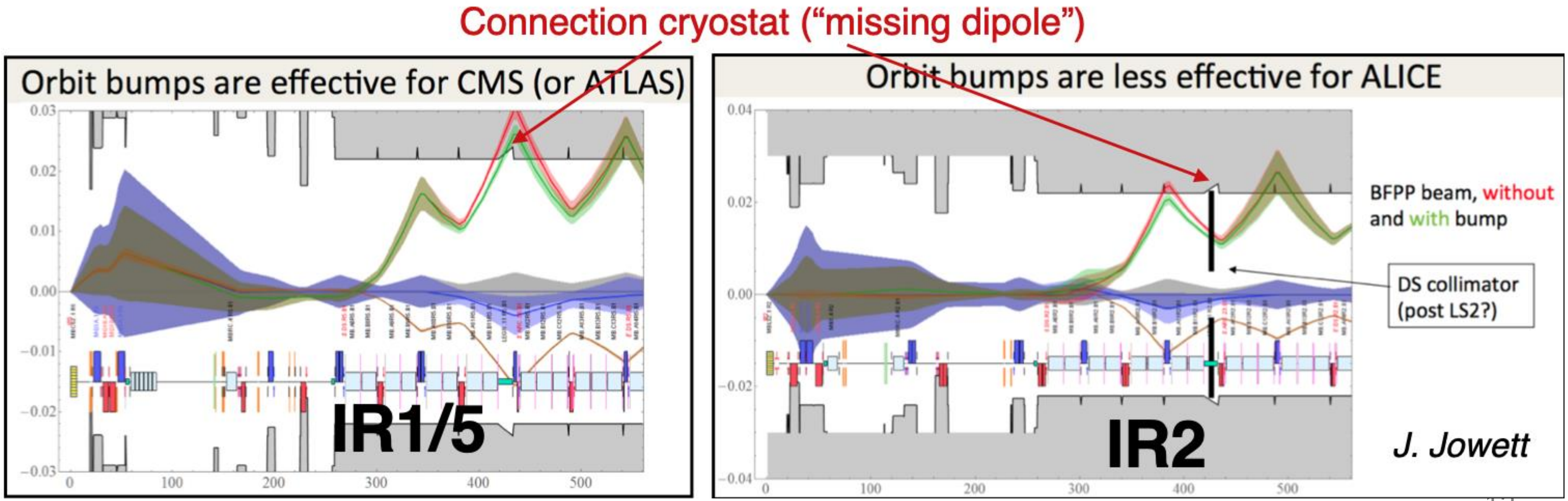
- **Running at 6.37 Z TeV instead of 6.8 Z TeV would add some margins**
  - Higher quench limit and lower stored energy

- **Choice between 6.8 Z TeV or 6.37 Z TeV beam energy**: tradeoff between different considerations
  - Higher beam energy: Higher luminosity due to smaller beam size (and potentially physics for ATLAS/CMS?)
  - Lower beam energy: Chance to have higher availability, if beam losses limit availability at higher energy
  - Analysis ongoing to understand implications of observed crystal cleaning performance
  - Experiments would like to fix one energy for the whole of Run 3
  - Commissioning time expected to be similar – anyway different cycle for ions
  - Expect decision early 2023

- **Even at 6.37 Z TeV, we would use crystal collimation** to profit from better cleaning

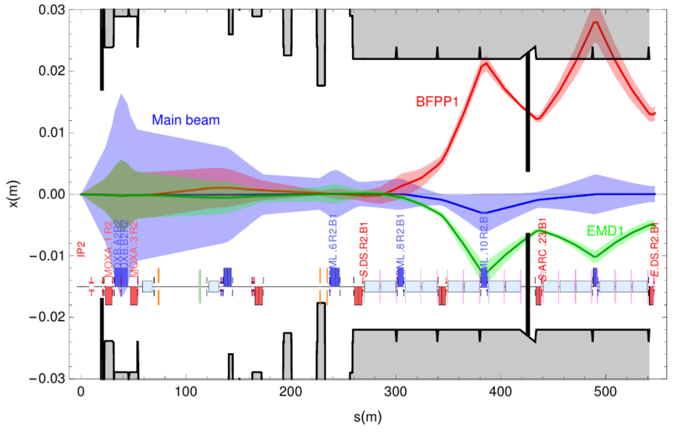
Alleviation of collisional losses

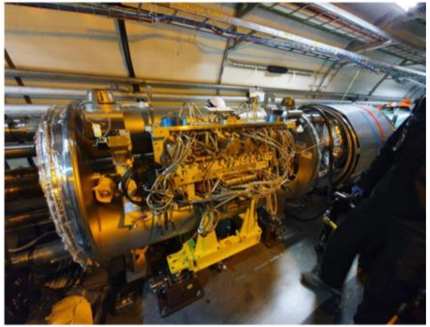
- Ultra-peripheral electromagnetic interactions create **secondary beams with changed charge-to-mass ratio**
  - In particular Bound-Free pair production, cause of one-electron ions – could quench a magnet below operational luminosity
- **IR1/5: Orbit bumps** successfully deployed already in Run 2 to steer losses into empty connection cryostat
  - By now, a well-established operational procedure
- **In IR2, bumps alone do not work**



IR2 dispersion suppressor collimation

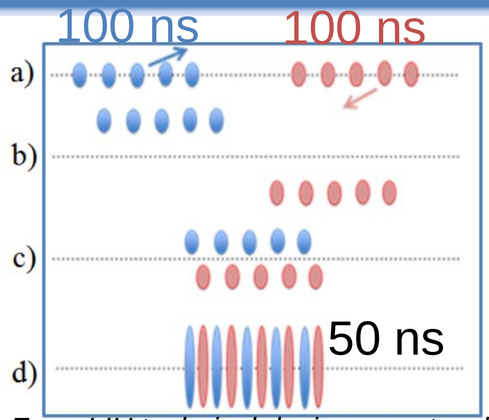
- **IR2 TCLD collimators installed in LS2**
  - Move losses with orbit bump from dipole in cell 10 to TCLD in cell 11 with orbit bump
  - Allows for requested factor 6 higher ALICE luminosity than in Run 2
- **Cleaning of BFPP losses by TCLDs demonstrated in 2022 ion test**
  - See talk D. Mirarchi
- **Vacuum spikes at the TCLD collimators under investigation**
  - Some spikes correlated with BLM signals, others present without beam
  - Need further follow-up with VSC for better understanding
  - RF fingers are overlapping on TCLD R2 – Xrays shown at LMC, correlation with spikes not demonstrated
  - Recent X-rays presented at Findings not believed to represent a risk for operation and no intervention planned (SY/STI)
  - TCLDs should be fully operational for the ion run



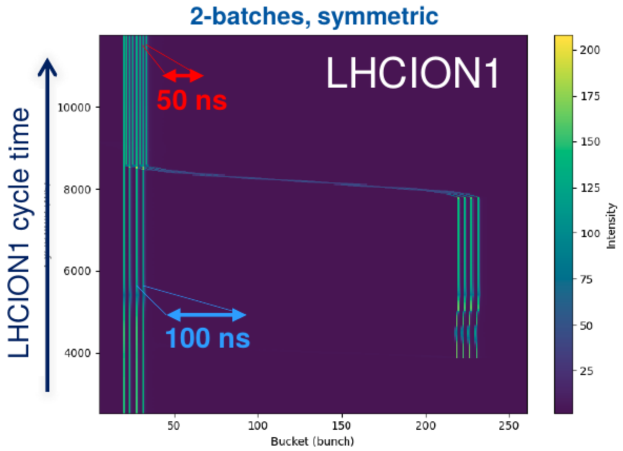


Slip-stacked beams

- SPS slip-stacking: **interleave two 100 ns bunch trains; create a 50 ns train**
- **8-bunch trains successfully used in 2022 Pb ion test**
  - Variations, but could reach intensity and emittance beyond LIU specification at LHC injection
  - Had first LHC collisions with slip-stacked beams
  - More details in talk D. Mirarchi
- **Filling schemes for 2023 rely on 56-bunch trains**
  - to be commissioned during 2023
  - Expect some brightness degradation compared to 8-bunch trains
  - 75 ns remains available as backup



From LIU technical design report, vol. 2



Beam parameters and filling schemes

- **Range of 50 ns Pb-Pb filling schemes available**
- **Final scheme to be selected by LHCC/LPC, variations during a run possible**
- **Projected Pb beam parameters in collision**
  - Based on LIU target for injection, with some degradation before reaching collision

Filling scheme	n.o. bunches	n.o. collisions at IP1/5	IP2	IP8	spacing
1240b_1240_1200_0	1240	1240	1200	0	50 ns
1240b_1144_1144_239	1240	1144	1144	239	50 ns
1240b_1088_1088_398	1240	1088	1088	398	50 ns
1240b_1032_1032_557	1240	1032	1032	557	50 ns
1240b_976_976_716	1240	976	976	716	50 ns
733b_733_702_468	733	733	702	468	75 ns

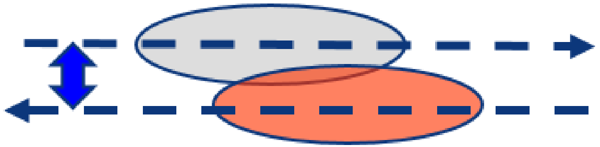
	LHC design	2018	Run 3
Beam energy (Z TeV)	7	6.37	6.8 or 6.37
Bunch spacing (ns)	100	75	50
Total n.o. bunches	592	733	1240
Bunch intensity (10^7 Pb ions)	7	21	18
Normalized transverse emittance (μm)	1.5	2.3	1.65

LHC optics configuration

- **Foresee similar optics as in 2018 Pb-Pb run** (S. Fartoukh)
  - different cycle from protons, squeezing also IR2
  - Configuration could stay similar for all years in Run 3-4
  - Study possibility of smaller β* and/or crossing angle in 2024-2025
  - ALICE spectrometer reversals expected

- **Luminosity levelling targets:**
  - L=6.4×10^{27} cm^{-2} s^{-1} for IP1/2/5
    - Could potentially be higher for IP1/5
  - L=1.0×10^{27} cm^{-2} s^{-1} at IP8
    - Could potentially be a bit higher – under study
  - Assuming separation levelling

	IP1	IP2	IP5	IP8
β^* (m)	0.5	0.5	0.5	1.5
crossing plane	V	V	H	H
spectrometer half crossing (μrad)	0	$\mp$72	0	-139
external half crossing (μrad)	170	$\pm$172	170	-170
net half crossing (μrad)	170	$\pm$100	170	-309
spectrometer polarity	-	pos/neg	-	pos

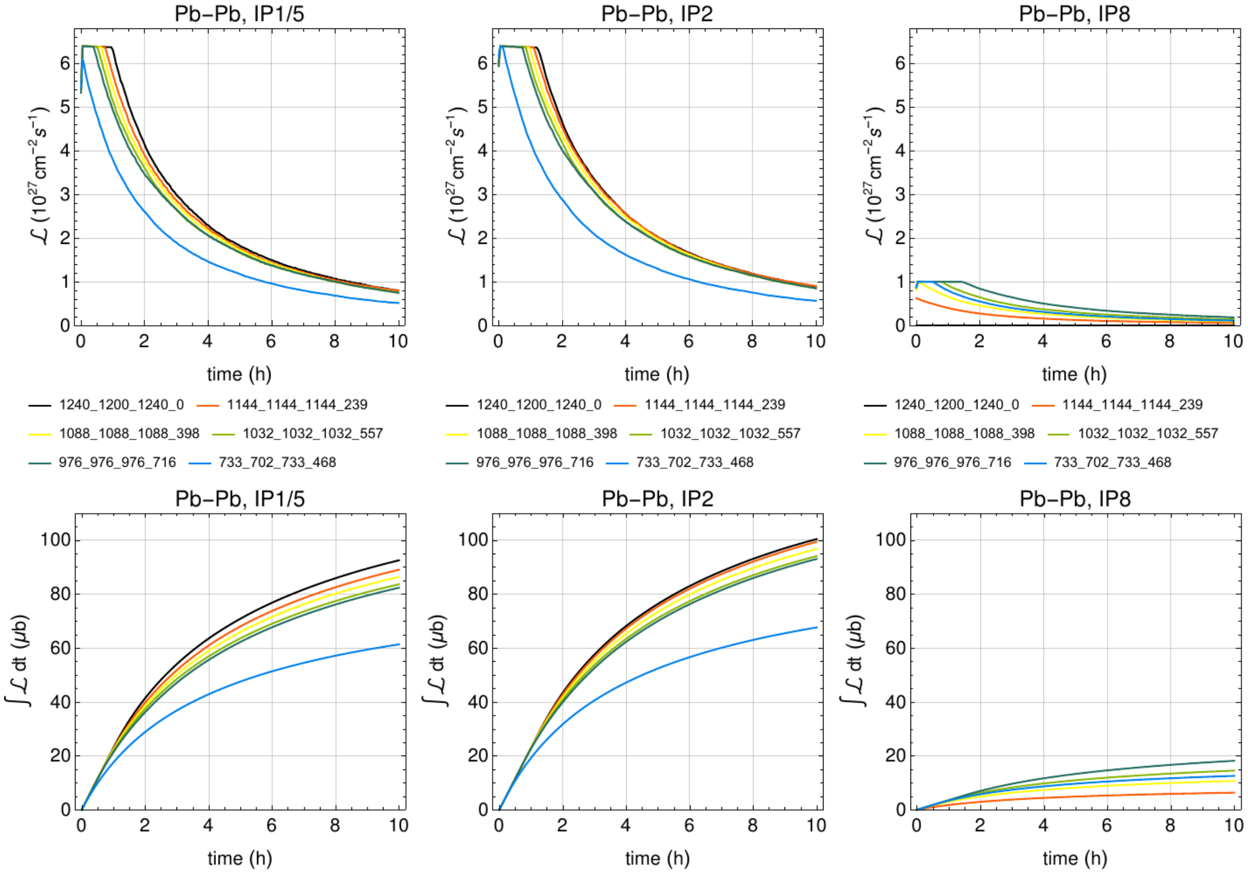


Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

Simulations of typical 2023 fill, Pb-Pb 6.8 Z TeV

- **Using projected LIU beam parameters** – might not be achieved immediately at the start
- **Single fill used to estimate projected 1-month performance**
  - For two energies
    - 6.8 Z TeV
    - 6.37 Z TeV
  - For two operational efficiencies
    - 50% (conservative, as used in proton projections)
    - 62% as in *LIU specification document*
- **Optimal fill length** of ~4.5h with ideal turnaround, goes up to 5.5h with achieved turnaround distribution from 2018



Reference: *EPJ Plus paper*

Projected 2023 performance, Pb-Pb

Integrated luminosity over **27 days in nb^{-1}**

6.8 Z TeV, 50%	IP1/5	IP2	IP8
1240_1200_1240_0	2.8	3.	0.
1144_1144_1144_239	2.7	3.	0.2
1088_1088_1088_398	2.6	2.9	0.33
1032_1032_1032_557	2.5	2.8	0.43
976_976_976_716	2.5	2.8	0.52
733_702_733_468	1.9	2.1	0.39

6.8 Z TeV, 62%	IP1/5	IP2	IP8
1240_1200_1240_0	3.5	3.7	0.
1144_1144_1144_239	3.3	3.7	0.24
1088_1088_1088_398	3.2	3.6	0.4
1032_1032_1032_557	3.1	3.5	0.54
976_976_976_716	3.	3.4	0.64
733_702_733_468	2.4	2.6	0.48

6.37 Z TeV, 50%	IP1/5	IP2	IP8
1240_1200_1240_0	2.7	2.9	0.
1144_1144_1144_239	2.6	2.8	0.18
1088_1088_1088_398	2.5	2.8	0.31
1032_1032_1032_557	2.4	2.7	0.42
976_976_976_716	2.3	2.6	0.5
733_702_733_468	1.8	2.	0.37

6.37 Z TeV, 62%	IP1/5	IP2	IP8
1240_1200_1240_0	3.4	3.6	0.
1144_1144_1144_239	3.2	3.5	0.23
1088_1088_1088_398	3.1	3.4	0.38
1032_1032_1032_557	3.	3.4	0.52
976_976_976_716	2.9	3.3	0.62
733_702_733_468	2.3	2.5	0.46

Considerations on performance

- **Estimated performance has large uncertainties**
  - Especially from machine availability and beam parameters in collision
- Depending on scenario, estimate about
  - 2.7-3.6 nb^{-1} at ALICE
    - Goal by experiment: 3.25 nb^{-1}
  - 2.4-3.2 nb^{-1} at ATLAS/CMS
    - Goal by experiment: 3 nb^{-1}
  - 0.3-0.5 nb^{-1} at LHCb
    - Goal by experiment: 0.4 nb^{-1}
- **The goals set by the experiments are challenging and ambitious**
  - Could be feasible, but also clear risk that we cannot reach the goals for some or all experiments
- **3-5% loss in integrated luminosity at 6.37 Z TeV**
- 25-30% loss in integrated luminosity with 75 ns filling scheme
  - Rough estimate of 50 ns intensity threshold below which 75 ns would be better: 80% of nominal intensity

Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

2023 Pb ion commissioning

- **Main steps of commissioning**
  - Optics through the cycle – different from the proton cycle, starting from the ramp
  - Transfer lines
  - RF capture, phases, phase loop
  - OP cycle setup (collisions, corrections…)
  - Collimation setup (Crystal collimation, experimental insertions)
  - Aperture measurements
  - Validation

- **In 2018 we had**
  - 1 day (3 shifts, spread out) of optics commissioning with protons, before the ion run
  - 4 days of scheduled commissioning in Pb-Pb period
  - 5.5 days of actual time used at start of Pb-Pb period
    - Including downtime and unforeseen issues

- **First rough estimate for 2023: need about 5 days in total, similar to 2018**
  - Might be optimistic – we will for the first time have operational crystal collimation and 56-bunch slip-stacked trains
  - We have only 4 days assigned – miss one day!
  - Could the optics be commissioned earlier with protons, as in 2018?

Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

MDs for the ion period

- **Several MDs proposed for the ion period**
  - We have one day of MD allocated for 2023 – clearly not all MDs can be done
  - Could postpone some to a later time in Run 3
- **BFPP luminosity quench** test to assess quench limits at experimental IRs from Bound Free Pair Production
  - Very good opportunity to assess steady-state quench limit – very stable and well-controlled source
- **Collimation quench test with crystals** to assess limit on beam loss power loads in IR7
- **Beam-beam studies** on the feasibility of smaller crossing angles
  - Goal: assess limits on crossing angle vs β*
- **Crystal collimation studies** for optimized configurations of crystals and standard collimators
- **Partially stripped ion tests** (part of the Physics Beyond Collider project)
  - study cleaning with crystal collimation for partially stripped ions; study beam lifetime and transmission through cycle
- **Collimation studies with lighter ions** (profiting from Oxygen run – 2024)
  - In view of possible future high-intensity operation with lighter ion species, study cleaning performance with crystals

future

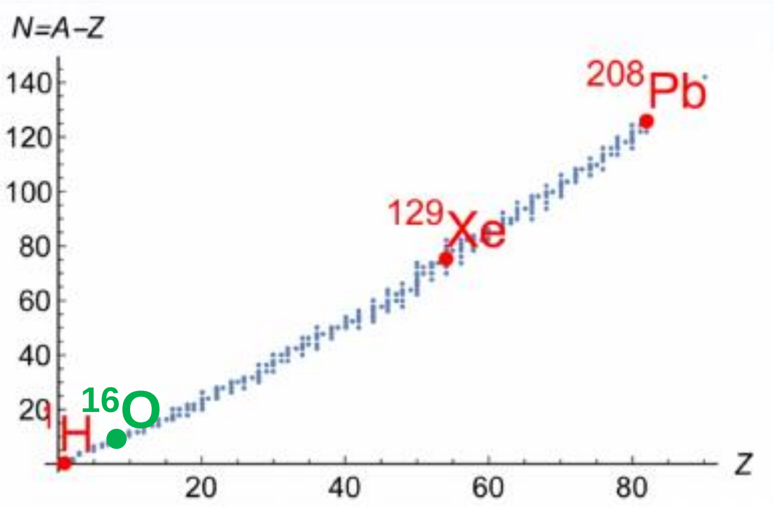
Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

Oxygen pilot run

- **O-O and p-O run scheduled in 2024**

- Motivations:
  - Physics interest from experiments
    - See talk F. Moortgat
  - Study limitations and performance, in view of proposed Run 5 high-intensity operation with lighter ions



- Wish list from experiments:
  - O-O: ~0.5/nb for ALICE, ATLAS, CMS
  - p-O: LHCb would like 2/nb, LHCf would like ~1.5/nb
  - LHCf requests low pileup of 0.02 in p-O (update: previously 0.01)
  - ALICE wants low pileup of 0.1-0.2

Oxygen run parameters

- **Target: about one week, low luminosity**
  - Most efficient: re-use machine cycle of the previous Pb-Pb
    - O-O run would be done at the same energy per charge as Pb-Pb
  - Use pilot beams with single injections (staying below 3×10^{11} charges per beam)
    - Minimizes validation time

- **Beam parameters at LHC (gu)estimated**
  - Only previous CERN-experience with O-beam: LEIR commissioning
  - Very hard to estimate what we will get in 2024 in the LHC
  - Options for intensity in collision / filling schemes,
    - 2E9 O/bunch, 18 bunches (12 collisions per experiment), 2.3 um emittance
    - 1.5E9 O/bunch, 21 bunches (14 collisions per experiment), 2.3 um emittance

- **Simulated luminosity performance for 6.8 Z TeV or 6.37 Z TeV beam energy**

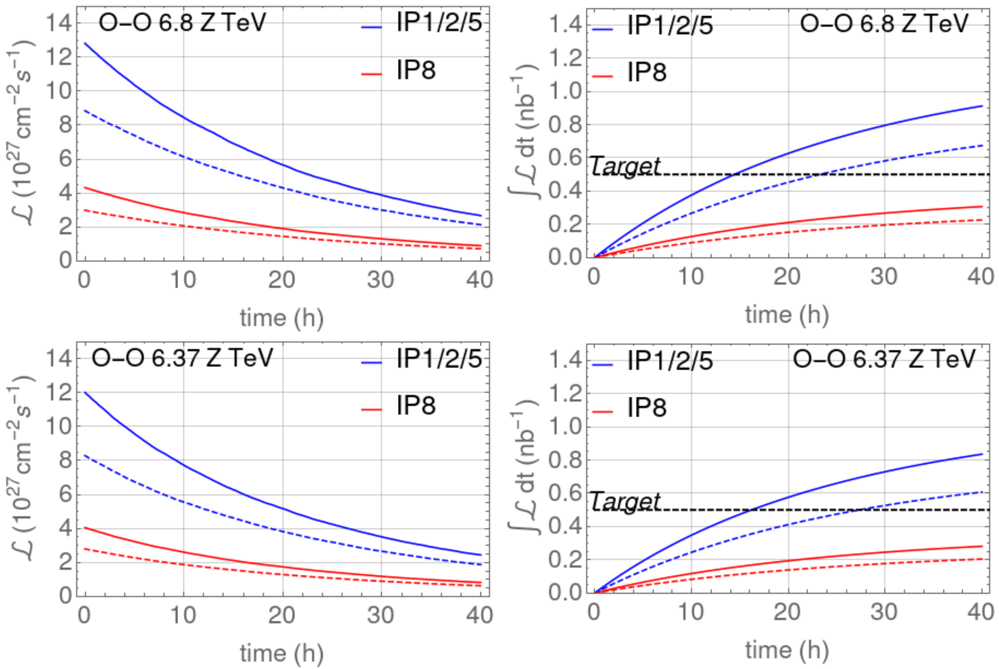
Performance with oxygen

- Simulations indicate we can reach
  - O-O targets in about a day, with 1-2 long fills
  - p-O targets in about 2.5 days
  - Large uncertainty applies!

- **Including commissioning time and contingency, could need 6-8 days**
  - Oxygen run seems a priori feasible and compatible with targets, but will certainly also be challenging

- Some work still remains: optimize machine configuration and filling schemes, study transmutation effect

Simulated performance O-O



Dashed lines: 21 bunches with 1.5×10^9 O/bunch ,
Solid lines: 18 bunches with 2×10^9 O/bunch
More details: See IPAC'21 paper

Outline

- Introduction and general plan for heavy-ion runs
- LHC machine configuration in the 2023 Pb-Pb run
- Performance estimates
- First thoughts on 2023 ion commissioning
- MDs for ions
- Oxygen pilot run
- Conclusions

Conclusions

- **Heavy-ion operation will continue in Run 3**
  - Operational periods at the end of 2023, 2024, 2025
  - Pb-Pb operation, p-Pb to be slotted in depending on Pb-Pb results

- **Pb-Pb run foreseen for 2023**
  - 27 days of physics, 4 days of commissioning scheduled
    - Commissioning seems tight – could consider commissioning optics already with protons as in 2018
  - Including 1-week p-p reference run and 1 day of MD

- **Run 3 machine scenario relies on several LS2 upgrades**
  - Slip-stacked 50 ns beams, new crystal collimators, dispersion suppressor collimators in IR2
  - Reaching full HL-LHC performance already in Run 3

- **Estimated performance for typical run (with 27 days of physics as in 2023)**
  - Pb-Pb: 2.4-3.6 nb^{-1} in ATLAS/ALICE/CMS, 0.3-0.5 nb^{-1} in LHCb
    - Could envisage to increase luminosity further through β*, crossing angle, levelling targets - need further feasibility studies

- **1-week oxygen pilot run foreseen for 2024**
  - Re-use existing Pb cycle, setup beam intensity
  - potential to reach experiment's targets in 6-8 days, but large uncertainties apply

Thanks for the attention!